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A taxonomy for emergency service station location problem

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Abstract The emergency service station (ESS) location problem has been widely studied in the literature since 1970s. There has been a growing interest in the subject especially after 1990s. Various models with different objective functions and constraints have been proposed in the academic literature and efficient solution techniques have been developed to provide good solutions in reasonable times. However, there is not any study that systematically classifies different problem types and methodologies to address them. This paper presents a taxonomic framework for the ESS location problem using an operations research perspective. In this framework, we basically consider the type of the emergency, the objective function, constraints, model assumptions, modeling, and solution techniques. We also analyze a variety of papers related to the literature in order to demonstrate the effectiveness of the taxonomy and to get insights for possible research directions.

Keywords Emergency service stations · Location planning · Taxonomy

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1 Introduction

The locations of emergency service stations (ESS) such as fire brigades, emergency service stations, ambulances, hospitals, police stations are of paramount importance in order to achieve an effective and reliable emergency response system. The fatalities and disabilities caused by accidents, fires, illnesses, pandemic diseases, natural disasters, etc. may be significantly reduced through an effective planning of the locations of these stations. As communities grow and demographics change, it may become necessary to replace existing ESSs or add more stations to satisfy the increasing public demands for emergency responses. Due to its characteristics and the advancements in the computing technology and Operations Research (OR) methods the location planning of ESSs have attracted substantial research efforts in the past four decades. However, the existing literature lacks a systematic classification of various types of ESS location problems and the papers that address them. Recently, [80] reviewed OR foundation in emergency response but this is rather a general review whereas we focus on the location planning in this study. Although [16,22,48] presented different classification schemes for the general location problem they provided a broad overview of location models rather than focusing on the characteristics of the ESS location problem. Besides, the literature has grown drastically since the 1990s, justifying the need for an up to date overview and classification of the articles. The objective of this paper is to fill that gap by presenting a taxonomic framework to define the problem domain and to classify the related papers based on their type, modeling, and solution approaches from an OR perspective. This framework will also enable us to identify the recent trends and potential research topics in this area.

ESS location problem has attracted the attention of many researchers and a vast amount of articles exists in the literature, mainly focusing on siting emergency medical stations (EMS) and ambulances. A comprehensive review may be found in [17,34,54]. On the other hand, research on locating fire stations is rather scant. Although the two problems are similar, fire stations may involve special features such as the risk factors associated with the demand points, varied vehicle types and equipments, location and relocation costs. Therefore, the problem of locating fire stations may require different approaches and methodologies. In general, OR methods have been employed to locate ESSs using primarily covering models. Optimal solutions to several problems described in the literature can be found by means of advances in computational capability and algorithmic approaches. However, more complicated problems of larger size require efficient heuristic techniques to obtain good solutions.

2 An overview of ESS location literature

2.1 A brief literature review

The basic deterministic Set Covering Problem (SCP) of [83] minimizes the number of stations covering all demand points at least once. Various approaches have been proposed to solve SCP and its special cases, e.g. [46] studies the dense instances and devise an approximation algorithm. [18] introduced the Maximal Covering Location

Problem (MCLP) to maximize the population or the number of demand points covered by with a limited number of stations. [73] developed the Tandem Equipment Allocation Model (TEAM) as an extension of MCLP. In TEAM, the objective is to maximize the population covered with two different service types where the number of stations for each type of service is limited. SCP, MCLP, and TEAM aim at maximizing the single coverage of demand points by the ambulances. In other words, if an ambulance is busy serving a demand point, other demand points covered by this ambulance will no longer be covered. To overcome this drawback, multiple coverage models have been proposed in the literature.

The Modified Maximal Covering Location Model (MMCLM) proposed in [20] maximizes the covered population and includes a second objective which maximizes the demand points covered multiple times. Two different variants of MMCLM were presented by [37]. In the first (BACOP1), the population covered at least twice is maximized within the same coverage standard given a limited number of stations. In the second (BACOP2), the objective function is to maximize the weighted average of, the demands covered once and multiple times. Capacitated MCLP with backup coverage was first studied by [56,59]. [31] formulated the Double Standard Model (DSM) which maximizes the demand covered multiple times using two different travel time restrictions. The objective is to maximize the demand covered at least twice in the shorter travel time limit.

The coverage of a demand point when the corresponding ambulance is busy responding a call has also been addressed using probabilistic models. In the Maximum Expected Covering Location Problem (MEXCLP) proposed by [21] identical busy probabilities are assigned to all ambulances and multiple ambulances may be located at a station. As an extension to MEXCLP, [68] developed two versions of the Maximal Availability Location Problem (MALP) where the objective is to cover each demand point with a given probability α. In MALP1, all ambulances are assigned the same busy probability whereas in MALP2 this restriction is relaxed and the minimum number of ambulances required at each demand point is estimated independently. [42] studied the problem of minimizing the number of ambulances required for a specified service level, by modeling the uncertainty in delay, travel time and ambulance availability. [64] developed a stochastic model where partial coverage is allowed. Busy probabilities were also studied by [11] where the ambulances were considered as servers in a queuing system by taking into account their inter-dependencies. [9] proposed the modified SCP which imposes a lower bound on the number of ambulances in order to achieve a certain reliability level. [53] also proposed a queuing probabilistic model as an extension to SCP. While the busy probabilities are identical in [11], [53] used location specific busy probabilities. Other extensions to MEXCLP were proposed by [33,66] by using time-dependent travel speeds.

The hypercube queuing model proposed by [49] has been used as a tool to estimate the coverage provided by different parameter settings, typically determined by an optimization model [71]. There are studies where the hypercube queuing model is incorporated in the optimization models and/or the solution methodology. [29,72] A review related to the use of hypercube queuing can be found in [30].

Although it might not be explicitly stated in most articles, we see that siting of fire stations attracted more attention in the early ESS location studies whereas recent literature mostly focus on the EMS and ambulance location and relocation problem. The location planning of fire stations using a coverage perspective was first addressed by [38] for the city of Bristol, UK. Early applications of siting fire stations are based on SCP and MCLP: [61,74,76]. [76] also considered the risk factors and proposed a model that provides double coverage for the regions with high risk. [54] extends MCLP to a probabilistic model that aims at maximizing regions covered by an engine and truck with a joint reliability of α. [7] present a multiple criteria modelling approach based on SCP and use goal programming to solve the fire station location problem in Dubai.

All the approaches discussed above are proposed for static (single-period) location planning of ESSs. In fact, there are only a few studies in the literature that attack the dynamic (multi-period) version. While [35,74] addressed the single coverage case as an extension of SCP and MCLP, [10] have recently investigated the backup double coverage which refers to the coverage within two distinct response time limits. Within the dynamic siting context, the relocation/redeployment of emergency vehicles was also considered in order to prevent regions left uncovered. While [46] developed a relocation system for fire brigades, [32] investigated the real-time redeployment strategies for ambulance services. Some recent articles that study the relocation of EMS vehicles include [63,75].

Similar to other combinatorial optimisation problems, the application of meta-heuristic approaches for solving the ESS location problem has gained more momentum recently due to the development of efficient methodologies. Among them tabu search [10,23,31,32,63], genetic algorithms [6,40,44,84], simulated annealing [81], and ant colony optimization [25,39,50] have received considerable attention. Finally, studies that utilize simulation for locating ESS include [27,28,36,40,55,66,70].

There certainly exist more articles addressing ESS location problem. However, the aim of this paper is not to review all of the literature but to develop a taxonomic scheme which would help us identify the underlying characteristics and fundamental features of the problem. In what follows, we report some statistical findings.

2.2 Statistical findings

We have looked at the academic literature in order to observe the general trend in terms of number of articles and journals. We did a search on Web of Science for certain journal titles and topics. The journal titles were assembled from the references of various well-known articles. As for the keywords, we used “location”, “coverage”, “emergency”, “ambulance”, “fire”, “police”, “patrol”, “disaster”, “hospital” and “medical” in various combinations for the titles and the subject. We have gone through the articles to choose the relevant ones. In total, we ended up with 210 articles that have been published since 1959. In spite of the fact that we may be missing some relevant articles or we may have articles that would not directly fit in the framework that we are interested in, we believe that this list fairly reflects the general trend. The articles span a range of areas including Operations Research/Management Science, Industrial Engineering, Economics, Health Sciences, Computer Science, and Civil Engineering. This also is an indication of the need for a unified classification of the articles related

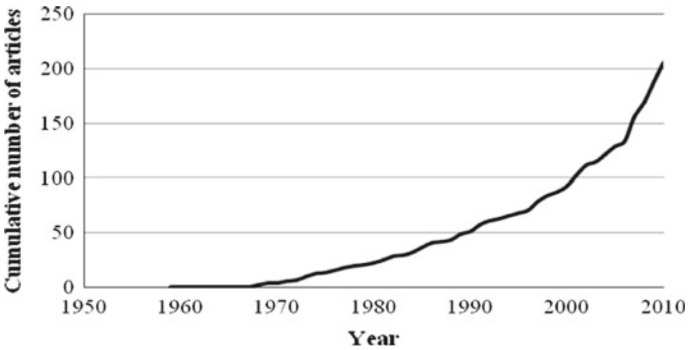

Fig. 1 Cumulative number of articles with respect to years

Table 1 Percentage of articles for each journal

European Journal of Operational Research	20.48%
Journal of the Operational Research Society	10.48%
Computers and Operations Research	10.48%
Socio-Economic Planning Sciences	6.67%
Management Science	5.71%
Operations Research	3.81%
Transportation Research Record	3.33%
Health Services Research	2.38%
Applied Mathematical Modelling	1.90%
Location Science	1.90%
Annals of Operations Research	1.90%
Decision Sciences	1.90%
INFOR	1.43%
Transportation Science	1.43%
Computers and Industrial Engineering	1.43%

to this topic. Figure 1 shows the cumulative number of articles with respect to years. We observe that there is growing interest in the subject especially after 2000. Table 1 shows the number of articles for each journal title for which there are at least three articles. We see that the top five journals in this list have published more than 50% of the papers analyzed.

3 Literature search process and taxonomy

The typical framework in many of the papers is to present a mathematical model that tries to maximize service with respect to resource constraints and minimize cost with respect to minimum service constraints. Then typically different solution methodologies are proposed to solve the problem. On top of this each model has its own set of assumptions and definitions in terms of objective(s) and constraints.

We scrutinized the articles that we used to produce the statistics in Sect. 2.2 in order to find the ones that would best fit to this typical framework. Finally, 57 papers were classified in the taxonomy in total. There are other important studies on ESS station location that would not fit into this framework. For instance, in some articles the goal is to estimate the travel times in different times of the day.

There are articles in the literature that present a taxonomy for various areas of research. For a discussion of how to build an effective taxonomy framework the interested reader is referred to [65]. We build our taxonomy tree with at most four levels from top to bottom in order to provide both simplicity and an ability to understand a broad range of features. Since a paper may belong to several different subcategories under the same category, the first and second level classifications are not strictly differentiating. In the first level of the classification tree, we discuss the general properties of the problem under the "Problem Type" heading. Then we have "Modelling" where we consider the basic components and assumptions of the model. Finally, we classify the articles according to the solution techniques used under the "Solution" heading. The whole classification tree can be seen in Fig. 2.

The first category is distinguished according to the type of emergency and general problem assumptions such as model structure, variation in time, and number of objectives. The type of the emergency can be fire, large-scale emergency/disaster, ambulance, hospital or police stations. There are also papers that discuss the emergency problems in a general way. The model structure of the ESS location problems can be deterministic or stochastic due to the objective function and/or constraints. Also the problem can be static or dynamic depending on whether certain parameters depend on time or not. We also distinguish short term and strategic planning problems. Finally, the articles are classified according to the number of objectives.

Then we classify the articles in terms of various model components and parameters. These include the objective function, parameters, type of decision variables, constraints, and type of the model. Mainly the objective of the ESS location problems can fall into two categories. Some models try to minimize the total cost while satisfying some minimum service requirements whereas others try to maximize service when the resources are scarce. "Total cost" and "Service" can be defined in different ways. The corresponding objectives could be minimizing the total number of facilities, the total distance or time to serve all calls, the sum of costs, the maximum travel time/distance to any single call or maximizing the (expected) covered area/demand once/multiple times, with a given probability or maximizing the probability of service being available within a specified distance etc. As one of the main parameters of the problem, the demand can be real or synthetic (randomly generated). The response data describe how coverage is defined and it depends on travel time or distance. Additionally, the server can be capacitated or uncapacitated. The server location can be determined in a discrete manner (e.g. choosing among existing station locations, all/chosen/except demand points) or a station can be opened anywhere in the feasible region (continuous). Furthermore, single or multiple types of servers can be located by specifying the total number of servers available. A few of the studies include costs about the location problem. If there is a constraint about the number of servers needed to serve a demand point, it is stated in the paper as a parameter. Also, in some of the stochastic location problems, busy fraction is taken into account, while reliability and queue

1. Problem Type
1.1. Type of Emergency
1.1.1. Fire
1.1.2. Large-scale Emergency/Disaster (Post-event)
1.1.3. Ambulance
1.1.4. Hospital
1.1.5. Police
1.1.6. General / not specified
1.2. Model Structure
1.2.1. Deterministic
1.2.2. Stochastic
1.2.2.1. Objective function
1.2.2.2. Constraints
1.3. Variation in Time
1.3.1. Static
1.3.2. Dynamic
1.3.2.1. Short-term (redeployment)
1.3.2.2. Long-term (strategic)
1.4. Number of Objectives
1.4.1. Single
1.4.2. Multiple
2. Modeling
2.1. Objective Function
2.1.1. Minimize the total number of facilities
2.1.2. Minimize the total distance or time to serve all calls
2.1.3. Minimize the sum of costs
2.1.4. Minimize the maximum travel time/distance to any single call
2.1.5. Maximize the covered area / demand once
2.1.6. Maximize the covered area / demand multiple times
2.1.7. Maximize the total area / demand covered with a given probability
2.1.8. Maximize the expected area / demand covered
2.1.9. Maximizing the probability of service being available within a specified distance
2.2. Parameters
2.2.1. Demand
2.2.1.1. Real demand
2.2.1.2. Synthetic demand
2.2.2. Response Data
2.2.2.1. Travel time
2.2.2.2. Distance
2.2.3. Server Capacity
2.2.3.1. Capacitated server
2.2.3.2. Uncapacitated server
2.2.4. Server Location
2.2.4.1. Discrete
2.2.4.2. Continuous space
2.2.5. Types of servers
2.2.5.1. Single
2.2.5.2. Multiple
2.2.6. Costs
2.2.7. Number of servers needed to serve demand point
2.2.8. Busy fraction
2.2.8.1. Sytem wide
2.2.8.2. Individual
2.2.9. Reliability
2.2.10. Queue size limit
2.3. Decision Variables
2.3.1. Coverage variables
2.3.1.1. Single
2.3.1.2. Multiple
2.3.2. Server assignment variables
2.3.2.1. Continuous
2.3.2.2. Binary / Integer
2.4. Constraints
2.4.1. Coverage constraints
2.4.1.1. At least once
2.4.1.2. At least multiple
2.4.1.3. Proportional
2.4.1.4. Mixed
2.4.2. Server capacity constraints
2.4.3. Priority of different types of servers
2.4.4. Maximum number of servers at each location
2.4.5. Maximum distance constraints
2.4.6. Upper bound on the number of assigned servers
2.5. Type of Model
2.5.1. Integer Programming
2.5.2. Dynamic Programming
2.5.3. Goal Programming
2.5.4. Fuzzy Programming
2.5.5. Non-Linear
2.5.6.Simulation
3. Solution
3.1. Optimal
3.2. Heuristic
3.3. Metaheuristic
3.3.1. Tabu Search
3.3.2. Ant Colony
3.3.3. Genetic Algorithm
3.3.4. Simulated Annealing
3.3.5. Others
3.4. Simulation

Fig. 2 Taxonomy of the ESS location problem literature

size limit can be used in dynamic problems. The decision variables of the model are generally single or multiple coverage variables changing according to the objective function, server assignment variables which can be continuous or binary/integer. Similarly, the coverage constraints depending on the objective function can be at least single/multiple, proportional or mixed ones. If the server located is capacitated, the model contains a constraint about the server capacity. Some models contain information about the priority of different types of servers. Also, the model can include a number of constraints such as an upper bound on different number of servers in each location and server assignment priorities. As the last feature of the model, we consider the type of the model which could be integer programming, dynamic programming, goal programming, fuzzy, non-linear programming or simulation.

The third category classifies the solution techniques of the problem. In certain articles, optimal methods are proposed mainly branch-and-bound whereas in others heuristic and/or metaheuristic approaches such as tabu search, ant colony optimization, genetic algorithm, simulated annealing, and others. Finally, simulation can be used as an alternative solution method for the ESS location problems.

4 The taxonomy

We used 57 of the articles representing different emergency location problems, modelling and solution methods. The articles used in the taxonomic review are listed in Figs. 3, 4. Empty cells mean that the paper doesn't involve any information about the specified attribute. On the contrary, if the cell is marked with "X", it means that the corresponding paper can be associated with that attribute. The gray filled columns highlight that a category has sub-categories, so they are not marked.

Although there are lots of blank cells in the taxonomic review, the unmarked attributes constitute only a small percentage, 1.52%, among all attributes. Also, the attributes marked only once, twice, and thrice times constitute 6.06%, 10.61% and 13.64%, respectively. These values indicate that our taxonomy is robust enough to systematically identify the literature about ESS location problem by showing that 82% of all the attributes are studied in at least two articles.

Among all the attributes, the only unmarked one is 2.5.2 which is "dynamic programming" type of the model. In fact, some problem types can be naturally modelled via dynamic programming approach. Yet, due to the size of the state space and stages, it would be quite difficult to solve the resulting models in reasonable running times.

The attributes marked once and twice in the taxonomy are 1.1.5, 2.1.8, 2.1.9, 2.2.4.2, 2.2.10, 2.3.2.1, 2.4.3, 2.5.3, 2.5.5, 3.3.4, and 3.3.5. This shows that "police" station location problems are not studied deeply in the literature. In general, the number of articles discussing deterministic models is greater than the ones including stochastic ones. Therefore, "maximizing the expected area/demand covered" or "the probability of service being available within a specified distance" are not widely used as objective functions in the problems. Furthermore, since "server location" is generally taken as discrete such as choosing among all the/specified/except or existing demand points, using continuous space to locate the servers is not common. Also, "queue size limit" is rarely used depending on the few number of queuing models in the literature. Mostly binary decision variables are used in the location literature, so using "continuous" server assignment variables constitutes a small percentage of the overall ESS location literature. Moreover, the problems generally contain single type of servers, thus the constraint of "priority of different types of servers" is not observed a lot in the articles. As the type of the model, "goal programming" and "non-linear" models are the least studied attributes in addition to the "dynamic programming". Simulated annealing turns out to be a less commonly used meta-heuristic compared to the tabu search, ant colony optimization, and genetic algorithm.

On the other hand, when we examine the attributes that are frequently marked we observe that most articles present a deterministic, static model with a single objective

Paper	1.	1.1.	1.1.1.	1.1.2.	1.1.3.	1.1.4.	1.1.5.	1.1.6.	1.2.	1.2.1.	1.2.2.	1.2.2.1.	1.2.2.2.	1.3.	1.3.1.	1.3.2.	1.3.2.1.	1.3.2.2	1.4.	1.4.1.	1.4.2.	2.	2.1.	2.1.1.	2.1.2.	2.1.3.	2.1.4.	2.1.5.	2.1.6.	2.1.7.	2.1.8.	2.1.9.	2.2.	2.2.1.	2.2.1.1.	2.2.1.2.	2.2.2.	2.2.2.1.	2.2.2.2.	2.2.3.	2.2.3.1.	2.2.3.2.	2.2.4.	2.2.4.1.	2.2.4.2.
1					X					X			X		X						X			X							X											X		X	
2			X										X		X					X				X												X		X				X		X	
3					X					X					X					X							X								X			X				X		X	
4								X		X					X						X				X			X	X							X			X		X			X	
5				X						X					X					X						X																			
6								X				X			X					X											X					X			X			X		X	
7			X							X					X						X				X	X	X												X	X			X		X	
8				X						X					X					X								X								X									
9								X					X		X					X						X										X		X				X		X	
10					X					X								X		X									X						X	X		X				X		X	
12			X		X					X					X					X				X				X							X				X			X		X	
13								X				X	X		X					X						X										X									
14								X		X					X					X								X											X			X		X	
15						X				X					X					X								X																	
19							X			X					X					X								X											X			X		X	
23					X					X					X					X								X							X			X				X			
24			X							X					X					X				X			X																	
25					X					X					X					X									X										X			X		X	
26					X					X					X						X			X			X		X						X			X				X		X	
31					X					X					X					X									X							X		X				X		X	
32					X					X							X			X									X							X		X				X		X	
35								X		X								X		X				X																					
36					X					X			X		X						X					X			X										X			X		X	
37								X		X					X					X									X						X				X			X		X	
38			X							X					X					X					X													X				X		X	
39			X							X					X						X						X	X										X				X		X	
40					X								X				X			X					X											X		X	X		X				
41					X								X				X			X																									
43				X						X					X					X					X			X											X			X		X	
44				X						X					X					X									X										X			X		X	
45								X		X					X					X								X								X			X			X		X	
47			X							X							X			X																		X				X		X	
50			X							X					X						X						X	X										X				X		X	
51			X									X			X					X										X									X			X		X	
52			X							X		X			X					X										X									X			X		X	
56			X							X					X					X									X						X	X			X			X		X	
57								X		X					X					X				X															X			X		X	
58			X							X					X					X						X									X	X			X		X			X	
59								X		X					X					X									X							X			X			X		X	
60			X							X					X					X								X							X	X			X		X			X	
61			X							X					X					X				X														X				X		X	
62					X					X					X					X										X						X			X					X	
63					X								X				X			X				X											X				X			X		X	
67								X		X					X					X								X																	
68			X										X		X					X										X					X			X				X		X	
69								X		X					X					X								X								X			X			X		X	
70					X															X												X						X							
74					X					X								X			X							X							X				X			X		X	
75					X					X							X			X									X						X			X			X			X	
76			X							X					X					X				X														X				X		X	
77					X					X					X					X								X							X			X				X		X	
78						X				X					X					X					X										X										
79								X					X		X					X								X								X			X			X		X	
81						X				X					X					X						X												X	X			X		X	
82					X					X					X					X									X									X				X		X	
83			X							X					X					X				X															X					X	
84			X							X					X						X					X	X										X				X			X

Fig. 3 Classification of the selected articles (attributes 1 through 2.2.4.2)

and a single type of uncapacitated server. The objective functions vary more although most of them are variations/extensions of the coverage or cost. We also observe that almost half of the articles use real data which is an indication that they are based on some project work.

Paper	2.2.5.	2.2.5.1.	2.2.5.2.	2.2.6.	2.2.7.	2.2.8.	2.2.8.1.	2.2.8.2.	2.2.9.	2.2.10.	2.3.	2.3.1.	2.3.1.1.	2.3.1.2.	2.3.2.	2.3.2.1.	2.3.2.2.	2.4.	2.4.1.	2.4.1.1.	2.4.1.2.	2.4.1.3.	2.4.1.4.	2.4.2.	2.4.3.	2.4.4.	2.4.5.	2.4.6.	2.5.	2.5.1.	2.5.2.	2.5.3.	2.5.4.	2.5.5.	2.5.6.	3.	3.1.	3.2.	3.3.	3.3.1.	3.3.2.	3.3.3.	3.3.4.	3.3.5.	3.4.
1		X											X				X			X												X					X								
2		X								X			X				X			X										X								X							
3		X											X				X										X	X		X								X							
4		X															X			X		X		X				X		X			X					X							
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Fig. 4 Classification of the selected articles (attributes 2.2.5 through 3.4)

5 Conclusion

In this paper, we presented a taxonomic framework for the ESS location problems. Although some classification schemes have been proposed for the general location problem no article in the literature provided a systematic classification of the ESS location problems. Our taxonomy categorizes the problems based on their type, modelling, and solution techniques from an OR perspective. Statistically, we observed that there is a growing interest to this problem, particularly after 2000. Most of the articles appeared in the European Journal of Operational Research, Computers and Operations Research, and Journal of the Operational Research Society (41%). To analyze the taxonomy we selected 57 articles that fairly reflected the general characteristics of the problems. The taxonomy is robust in the sense that only 1 attributes out of 65 remained unmarked and 18% of the attributes included were marked twice or less.

The results revealed that EMS and fire station location problems have been extensively studied whereas hospital and police station location problems have been rather neglected. This may be due to the fact that these two problems involve other characteristics and criteria that make it difficult to study them from an emergency covering perspective. In addition, we observed that dynamic programming, goal programming, and non-linear models have been rarely used. Since stochastic/queuing approaches are scant, related objective functions (such as maximizing the expected area/demand covered or the probability of service being available within a specified distance) and constraints (such as queue size limit) are also rarely observed in the taxonomy. It is surprising that although locating ESS is a strategic, long-term decision multi-period models have not received much attention. When we investigate the solution methodologies, we see that meta-heuristic methods have attracted more attention in recent years; however, these methods were limited to the well-known genetic algorithms, tabu search, ant colony optimization and there is potential for applying newly developed efficient techniques.

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